# Evolution Operator-based Automata Control approach for EMS in Active Buildings

***Trinadh Pamulapati*, Adib Allahham, Sara L. Walker, and Damian Giaouris***

*School of Engineering, Newcastle University, Newcastle upon Tyne, UK*
**email: trinadh.pamulapati@newcastle.ac.uk*

**Keywords**: AUTOMATA, EVOLUTION OPERATOR, ACTIVE BUIDLINGS, ENERGY MANAGEMENT

## Abstract

Active buildings (ABs) are flexible assets that can exploit the advantages of renewables and energy storage to meet their own needs as well as have a positive impact on the grid. In order to control such systems, several Energy Management Strategies (EMS) have been proposed, with automata being a very promising one. Unfortunately, when several ABs are being combined with various operating restrictions imposed on them, these control methods will require high processing power and can become cumbersome to operate particularly in an adaptive mode. In this paper, we propose for the first time to enhance automata with a new method that utilizes evolution operators. In this work, it is proposed that the evolution operators will be used to express the guard conditions of the automata, and hence allow the transition from one operating state to another, to be more flexible, and versatile. This will allow us to control large and complex energy systems and will maximise their efficiency and lifetime. As a case study, and to clearly show the merits of proposed methodology, a simple AB is considered, and we demonstrate with an example of how easily we can adaptively modify the EMS when this is required.

## 1. Introduction

The UK is targeting the transition to net-zero carbon emission by 2050 [1], and to achieve these goals, buildings with active characteristics play a pivotal role [2]. ABs that are energy positive in nature are becoming an integral part of modern distribution power system along with virtual power plants, and microgrids. The trend of having local renewable energy (RE) generation (such as PV), energy storage systems, smart operation of various assets/loads such as Electric Vehicles (EVs) and thermal loads, make ABs as the essential part of the low voltage distribution network [3]. Therefore, the efficient EMS or controls for buildings that make them energy neutral or even offer services to the grid are beneficial. Furthermore, they can substantially reduce installation of ancillary power sources, avoid congestion, provide various services to the grid, and able to improve system reliability [4].

Optimization-based EMS are efficient and consider various economic operational conditions [5]. However, due to the non-linear, non-convex mathematical modelling and complexity, reaching the optimal solution need high computational effort. In contrast to it, predetermined EMS are mainly developed for real time operation and are based on understanding the system's operation [6].

EMS for microgrids are modelled using different control methods such as simple if-else rules as flowcharts, supervisory control (SC) [7], [8], model predictive control [9], multi-agent systems [10], and other generic methods [11-14]. Among them, the traditional control methods such as if-else rules in the form of flowcharts [15, 16] can result in complicated control strategies for ABs and microgrids.

Finite state automata are well used to model a system with multiple operating states and give better results than traditional if-else strategies [17]. In [18], a virtual power plant was modelled using Hybrid Automata (HA). The finite automata to implement and instantiate EMS is proposed in [19], and it is used in an integrated framework that was developed for sizing and energy management of hybrid energy systems. Recently, in [20] a hybrid automata-based EMS for a microgrid that combines propositional-based logic to make transition between several operating states of the system assets is used.

In parallel to this work, in [6] it was developed a new method based on the so-called evolution operators in a state space graph-based systems approach, for the management of multi-vector microgrids. This has greatly simplified the way that EMS are presented, optimised, and offered a valuable tool into the more efficient operation of smart grids.

In this paper, we are proposing for the first time to combine the idea of using evolution operators in conjunction with automata in order to have an efficient way to describe an EMS of an AB. This combined approach of automata with evolution operators provides a better EMS for ABs that hope to provide less complex and easy to control energy systems that are adaptable and flexible. The contributions of this work are:

1. A novel idea of implementing EMS with evolution operator incorporated automata for ABs.
2. In comparison to the conventional if-else rules or forward/backward state verification, proposed approach reduces computational complexity as it avoids repetitive search among the possible states of a system.
3. These control strategies can be used in support with high-level optimization approaches.

This paper is organised as follows. In Section 2, the background details of automata and evolution operators are briefly presented. Finite automata, evolution operators used, control strategy proposed for a simple system (AB with PV and battery) are presented in detail in Section 3. The verification and qualitative analysis of the resultant EMS at every time instant is provided in Section 4. The conclusions and future extensions are briefly presented in Section 5.

## 2. Background

### 2.1. *Automata*

In general, automata are used to model the number of discrete operating states of a system with different sub-components [21, 22]. Finite automata consider dynamic relation between all the system components [23]. Therefore, it can be used for state transitions from one to another. In other words, the implementation and instantiation of EMS can be performed on a considered system using automata. Modelling of EMS using automata with a system having several assets have advantages [19] such as 1) small and simpler system models for assets reduce complexity, 2) easy modification capability as it is a graphical based illustration, 3) possibility of parallel state transition, 4) adaptability to system changes.

The automata that can handle a system: a) having only discrete finite states called Finite Automata (FA), b) having both discrete and continuous state variables are called Hybrid Automata (HA) [24]. These are represented by (1) in Section 2.2. The normalized SOC value of battery is an example of a continuous state variable which varies between 0 and 1.

### 2.2. *Finite automata and hybrid automata*

The FA and HA can be defined using the following equation:

$$FA = (Q, \Sigma, G, q_0, F),\ HA = (Q, X, f, D, E, G, R)$$

*where:*

$Q = (q_1, q_2, \ldots, q_n)$ = *set of discrete states in the system*
$q_0$ = *initial state,* $F$ = *Final state,* $\Sigma$ = *finite set of inputs*
$X$ = *set of continuous states,* $f$ = *vector field of* $X$
$D \subseteq Q \times X$ = *Domain of the system. i.e., invariant set*
$E = Q \times Q$ =*No. of edges between the discrete states Q.*
$G$ = *Guard conditions to enable the transition between two discrete states* $q_x, q_y \in Q$
$R$ = *Reset condition during the state transition.*

As an example, in Fig.1 two discrete states (Q) representation for a simple photovoltaic (PV) generation based on solar irradiation can be represented in two states: no PV output (state $q_1$) and PV output (state $q_2$). Here the transition between each state happens when the guard condition satisfies i.e., irradiation on solar cell more than its minimum required irradiation to produce power.

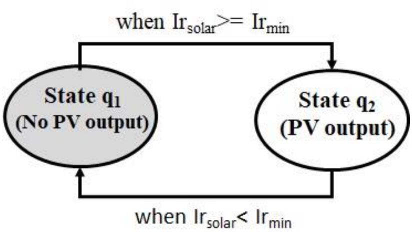


*Figure 1. An example of PV states*

### 2.3. *Evolution operators*

In EMS for systems like ABs, microgrids, or VPPs the EMS can be incorporated into the evolution operators [6]. These evolution operators are usually a combination of logical operators on Boolean variables associated with state variables of the graph that represents the system. The state transition in automata occurs in response to the evolution operators. For more understanding on how this can be implemented, please refer to [6].

## 3. Proposed Methodology

### 3.1. *Building with active nature*

The case study chosen in this work is a building connected to distribution feeder that can provide required energy at any time of a day, shown in Fig.2. The system was specifically chosen to be simple in order to highlight the merit of the proposed work. More specifically, the building is having a battery, own PV generation that can supply its load and the surplus can be fed to distribution system. In this work, the assumptions made are, when there is a surplus (deficit) of power then it is used to either charge (discharge) the battery or fed to (from) the distribution system but not both, at the same time. In this work, the losses due to the converter operations are ignored.

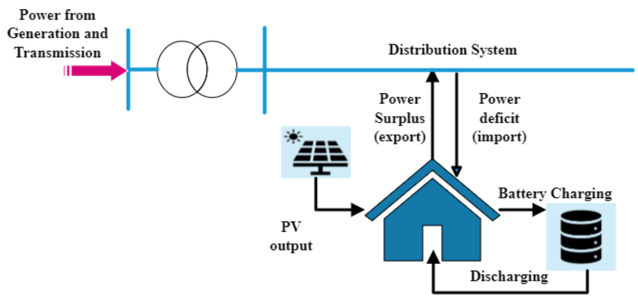


*Figure 2. Considered building system with PV and battery*

### 3.2. *Automata states:*

As shown in Fig.2, the operating state of the system at time t, depends on available solar power, required load demand, and battery SOC. Therefore, the system may be in a state of power surplus or deficit, along with battery charging or discharging. To obtain reachable and non-reachable states of the considered system, modelling of each subsystem using finite automata and performing parallel composition results in total of 12 states (0-11).

*Table 1: Possible total states of the system obtained using Automata*

| **State: 0** | **State: 1** | **State: 2** | **State: 3** |
|---|---|---|---|
| PV: OFF | PV: OFF | PV: OFF | PV: OFF |
| Load: ON | Load: ON | Load: ON | Load: ON |
| Grid: Import | Grid: Import | Grid: Import | Grid: Export |
| Bat: Idle | Bat: Charge | Bat: Discharge | Bat: Idle |
| **State: 4** | **State: 5** | **State: 6** | **State: 7** |
| PV: OFF | PV: OFF | PV: ON | PV: ON |
| Load: ON | Load: ON | Load: ON | Load: ON |
| Grid: Export | Grid: Export | Grid: Export | Grid: Export |
| Bat: Charge | Bat: Discharge | Bat: Discharge | Bat: Charge |
| **State: 8** | **State: 9** | **State: 10** | **State: 11** |
| PV: ON | PV: ON | PV: ON | PV: ON |
| Load: ON | Load: ON | Load: ON | Load: ON |
| Grid: Export | Grid: Import | Grid: Import | Grid: Import |
| Bat: Idle | Bat: Discharge | Bat: Charge | Bat: Idle |

From each state 4 possible states can be reached via a single event transition. All possible 12 states and their description are given in Table 1.

The modelling of each component of system (PV, grid, battery, and load) and whole states, their transitions, event condition are clearly shown in Fig.3. By default, we considered that the load is always ON and present in every state of the system. For better illustration, the representation of load (black lines), conditions to remain in same state for each component are ignored in Fig 3.

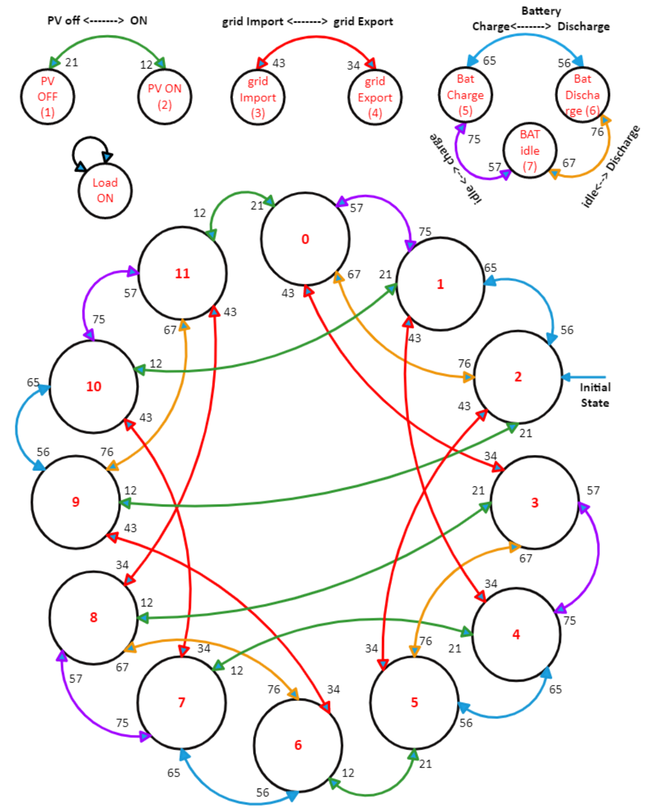


*Figure 3. Automata states and their transition conditions*

Only one of the two transition condition are shown on each coloured line will be active during a state transition from one to another. For example, at state 0, PV is OFF and when PV is ON, the transition condition (Green-12) satisfies, and system now move to state 11.

Therefore, it is understood that a simple system shown in Fig.2 has 12 possible states and 48 state transition conditions as shown in Fig.3. Whereas for bigger systems with several components, the number of states will drastically increase and need to check numerous state transition conditions. This is computationally expensive. To develop reconfigurable, extendable EMS, easily adaptable, and verifiable conditions for state transitions, we are proposing the combination of automata along with evolution operators as guard conditions to the transition from one state to another.

### 3.3. *Evolution operator control strategy*

In the considered AB, the system operation affected by the active components, the available power to satisfy the load, and the available energy in the battery. To describe these statements, we define three Boolean variables as [3]:

$$\rho_1 = [P_{net}(t) > 0],\ \rho_2 = [SOC(t) < SOC_{\max}]$$
$$\rho_3 = [SOC(t) > SOC_{\min}]$$

*where,* $P_{net}(t) = P_{PV}(t) - P_{Load}(t)$

Hence now, we can define the four evolution operators $\varepsilon_i, (i = 1,2,34)$ as:

$$\varepsilon_1 = \rho_1 \wedge \bar{\rho}_2,\ \varepsilon_2 = \rho_1 \wedge \rho_2,\ \varepsilon_3 = \bar{\rho}_1 \wedge \bar{\rho}_3,\ \varepsilon_4 = \bar{\rho}_1 \wedge \rho_3$$

### 3.4. *Methodology of building the EMS*

To develop EMS and their transition for the considered system, the proposed methodology is presented in Fig.4. As step 1, we model each component of system using automata. By performing parallel composition, the reachable states and their transition conditions are obtained. In step 2, the expert/system operator input is considered to obtain a desired number of operating states and conditions. In step 3, based on expert input, the guard conditions are formulated using evolution operators as shown in Section 3.3. Finally, we combine the finite automata states obtained from steps 1 & 2 and use evolutionary operators formulated in step 3 as guard conditions (in step 4) to EMS state transition from one to another. The main novelty of this type of implementation is to provide a) easily reconfigurable- by modifying any sub system operation (shown in Section 4: Scenario-2), b) extendable- adding of any additional components such as diesel generator, fuel cell to the existed system (Section 5: Future Work), and c) interactive (from operator/user inputs), EMS for ABs.

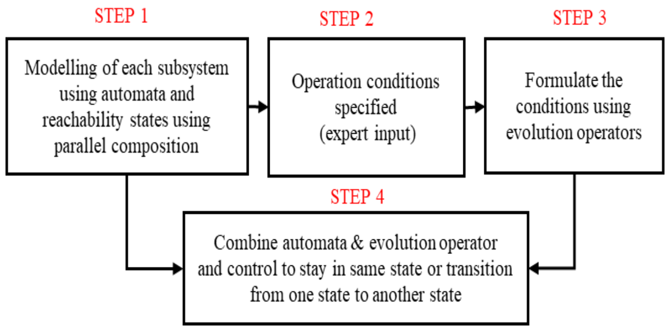


*Figure 4. Methodology for EMS transition in a system using automata with evolution operator*

More specifically, with desired operation and expert input, the four operating EMS states in this simple system obtained using procedure shown in Fig.4 are:

***State q₁:*** When the AB is in power surplus mode ($P_{PV}(t) > P_{Load}(t)$) and battery is at its maximum capacity ($SOC(t) = SOC_{max}$);

***State q₂:*** When the AB is in power surplus mode ($P_{PV}(t) > P_{Load}(t)$) and battery isn't fully charged ($SOC(t) < SOC_{max}$);

***State q₃:*** When the AB is in power deficit mode ($P_{PV}(t) < P_{Load}(t)$) and battery unable to supply the load ($SOC(t) \leq SOC_{min}$);

***State q₄:*** When the AB is in power deficit ($P_{PV}(t) < P_{Load}(t)$) and battery can supply the load ($SOC(t) > SOC_{min}$);

The control algorithm for ABs that uses the above evolution operators are presented in Algorithm 1.

**Algorithm 1:** *Evolution operator incorporated automata control strategy:*

**Input:** PV output, initial state of the system *($q_0$)*

**Output:** SOC of battery, state of system and power flows.

**Step 1:** input the PV and load profile data for the required control period ($T$= 24 hours, time step ($\Delta t$ = 1 hour)
**Step 2:** calculate the power surplus or deficit *($P_{net}$)*
**Step 3:** calculate the Boolean variables that quantify the state of the graph, $\rho_1, \rho_2, \rho_3$.
**Step 5:** evaluate evolution operator *($\varepsilon_i$)* to initiate state transition of the system to a new state $q_i$.
**Step 6:** battery should charge or discharge or keep idle state depend on the Step 5.
**Step 7:** repeat the process for the whole period and calculate all the power flows.

## 4. Results and Analysis

The considered AB model simulation is simulated in MATLAB environment and the PV generation, load profiles for a 24 hour time period with time step of 1 hour is taken form [25, 26]. A battery of size 10 kWh is considered in the present work, and it is assumed that the battery charge with $P_{net}$ (when surplus) and discharge $P_{net}$ (when Deficit) to the load considering maximum and minimum SOC limits. The initial, minimum, maximum SOCs, and both charge, discharge efficiencies of battery are considered as 0.5, 0.3, 0.9, and 1 respectively.

Scenario 1: *Proposed approach on original system*: Figure 5 shows the plots (colour: Blue) for AB state estimation and the actions that the energy management control strategy takes at each hour. Figure 5(a) shows the load and PV generation profiles for 24 hours. It is observed that the PV generation is more than the load requirement at time instances between $t$ = 11th and 16th hour in the considered day, and correspondingly, the system may be state $q_1$ or state $q_2$ during this time. It will be dependent on the battery SOC in the previous *(t-1)* and current time instance *(t)*, load, and PV generation. In Fig.5(b), the SOC values of the battery from $t$ = 1 to $t$ = 24 are plotted. Furthermore, when the system is operating in state $q_2$, battery charges from the excess available PV generation. And in state $q_4$, battery discharges to supply the balance AB load. Figure 5(c) shows the states of the building for the whole day when evolution operators are used as the control logic. During surplus mode ($P_{net}$ >0) the battery is charged with the power available from PV, therefore the building is operating on state $q_2$. If battery reaches its maximum SOC then surplus power fed to the distribution system and AB operating state is $q_1$. When deficit, it operates on State $q_3$, or State $q_4$ depend on the SOC of battery. When system is in State $q_3$, importing power from the distribution gird to satisfy the load demand. Overall, using evolution operators-based rules to implement the EMS for an AB, that allow transition from one state to another operating states are successfully developed and verified.

Scenario 2: *Proposed approach with reconfigurable EMS:* The methodology presented above based on HA is well known to be very efficient in describing EMS of microgrids **[20]**. Having said that, when the authors have implemented similar EMS on a real system, built in Xanthi Greece [3], it was observed that the EMS needed to be constantly updated in order to increase the system's autonomy from the main grid. As an example, it was observed that sometimes (under specific load/weather conditions) it was beneficial for the system to allow the battery to get to lower values of SOC than normal. This was particular true when various assets for the system presented in [3] where being activated in order to provide extra energy to the system while it was just a few hours before the PVs were to generate large amounts of energy. So these assets were overutilized and should not have been activated. This specific situation will be studied here. More specifically, in order to demonstrate the enhanced automata using the aforementioned evolution operators, we will enhance the EMS by allowing the system to work on lower values of SOC if there is a forecast for high PV output a few samples after the SOC has dropped below 0.3. This can easily be achieved by using the following change in Boolean variable $\rho_3$ of the evolution operators $(\varepsilon_3, \varepsilon_4)$ as a guard condition:

$$\rho_{3+} = \rho_3 \vee (\rho_1' \wedge \rho_{pv})$$

where $\rho_{PV} = \left[P_{PV}^{For}(t+1) > P_{PV}^{Thr}\right] \wedge \left[P_{PV}^{For}(t+2) > P_{PV}^{Thr}\right]$, with $P_{PV}^{For}$ is the forecasted PV output and $P_{PV}^{Thr}$ is a predefined threshold (which can be time dependent and adaptive in general). Hence, if a forecasting tool has predicted that the PV generation is going to be high enough for next two consecutive 2 samples then $\rho_{PV}$ will be 1 and hence the battery will be discharged below 30%.

The important thing to note here is that the automata states and operation will not be affected by this change and hence the overall EMS will remain the same. On the other hand, by doing this small change to the guard condition it is possible to greatly enhance the system's operation. As it was presented in [3], for a system not operated with automata, this can greatly enhance the microgrid's operation. In this paper we combined the results in [3] with automata and we show that the adaptability of the evolution operators can also be useful in ABs.

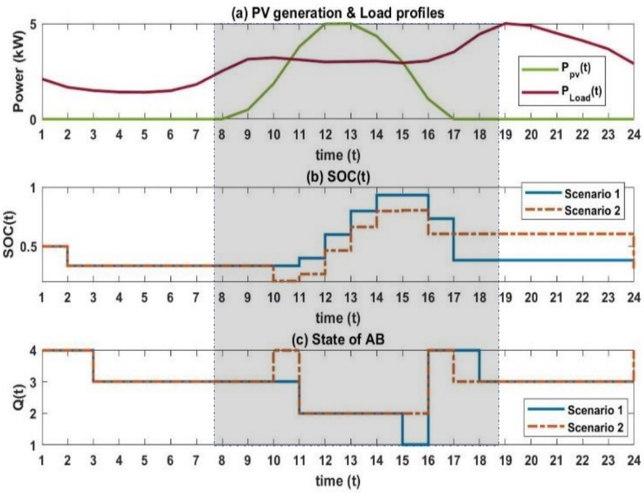


*Figure 5: Evolution operator-based control strategy for an AB for both Scenarios 1 & 2: a) PV and load profiles, b) SOC of battery at time t, and c) AB state of operation*

The results obtained by considering the PV forecasted information plotted in dotted line (colour: Orange) of Fig.5. The highlighted part in the Fig.5 shows at $t$ = 10th hour, even though the $P_{net}(t) < 0$, due to more PV output in the next two instances, the battery discharges from its SOC of 0.3 to maximum discharge SOC of 0.2. At $t$ = 10, the EMS changes from state $q_3$ to $q_4$ for short time and avoided the power intake from the distribution system. From $t$ = $16^{th}$ hour, battery is no longer discharges since load power requirement is more than the battery capacity that it can supply (to avoid battery discharge more than minimum SOC limit of 0.3) and no more PV output is observed in the coming two consecutive time instances.

## 5. Conclusion

The basic idea of evolution operator in conjunction with simple finite state automata approach is presented for an active building. The system transition through the different states by using these control rules is presented and verified. Also, an extended case study to show the flexibility in modifying evolution operators to change the systems behaviour is presented. The limitations of if-else rule based logical operations in terms of a greater number of sub system components and their interactions can possibly avoided through the proposed method. Though the considered system is simple and have basic AB components such as PV and battery, the evolution operator incorporated automata is first of its kind to be applied and can be a potential method for implementing EMS in ABs with more components. In addition, the demand response and forecasting information incorporation will be easier than the simple if-else rule-based control strategies.

**Future work:** The proposed method can be developed and extended to ABs or microgrids with various sources such as wind turbines, controlled heating systems, electrolysers and fuel cells, a diesel generator, and loads with different characteristics, preferences. This low-level control strategy can be incorporated within a high-level optimal EMS.

## 6. Acknowledgements

The authors wish to acknowledge funding from the Industrial Strategy Challenge Fund and Engineering and Physical Sciences Research Council, EP/S016627/1, for the Active Building Centre research project.

## 7. References

[1] H. Government, "The ten point plan for a green industrial revolution," ed: HM Government London, UK, 2020.

[2] G. Strbac, M. Woolf, D. Pudjianto, X. Zhang, S. Walker, and V. Vahidinasab, "The role of active buildings in the transition to a net zero energy system," *Active Building Centre Research Programme,* 2020.

[3] S. Nikkhah, A. Allahham, J. W. Bialek, S. L. Walker, D. Giaouris, and S. Papadopoulou, "Active Participation of Buildings in the Energy Networks: Dynamic/Operational Models and Control Challenges," *Energies,* vol. 14, no. 21, p. 7220, 2021.

[4] M. Gržanić, T. Capuder, N. Zhang, and W. Huang, "Prosumers as active market participants: A systematic review of evolution of opportunities, models and challenges," *Renewable and Sustainable Energy Reviews,* vol. 154, p. 111859, 2022.

[5] S. Nikkhah, A. Allahham, M. Royapoor, J. W. Bialek, and D. Giaouris, "Optimising Building-to-Building and Building-for-Grid Services under Uncertainty: A Robust Rolling Horizon Approach," *IEEE Transactions on Smart Grid,* vol. 13, no. 2, pp. 1453-1467, 2022.

[6] D. Giaouris, A. I. Papadopoulos, C. Patsios, S. Walker, C. Ziogou, P. Taylor, S. Voutetakis, S. Papadopoulou, and P. Seferlis, "A systems approach for management of microgrids considering multiple energy carriers, stochastic loads, forecasting and demand side response," *Applied energy,* vol. 226, pp. 546-559, 2018.

[7] A. Ghasaei, Z. J. Zhang, W. M. Wonham, and R. Iravani, "A discrete-event supervisory control for the ac microgrid," *IEEE Transactions on Power Delivery,* vol. 36, no. 2, pp. 663-675, 2020.

[8] A. Kharrazi, Y. Mishra, and V. Sreeram, "Discrete-event systems supervisory control for a custom power park," *IEEE Transactions on Smart Grid,* vol. 10, no. 1, pp. 483-492, 2017.

[9] M. Arnold, R. R. Negenborn, G. Andersson, and B. De Schutter, "Model-based predictive control applied to multi-carrier energy systems," in *2009 IEEE power & energy society general meeting*, 2009: IEEE, pp. 1-8.

[10] M. W. Khan, J. Wang, M. Ma, L. Xiong, P. Li, and F. Wu, "Optimal energy management and control aspects of distributed microgrid using multi-agent systems," *Sustainable Cities and Society,* vol. 44, pp. 855-870, 2019.

[11] D. Giaouris, A. I. Papadopoulos, P. Seferlis, S. Voutetakis, and S. Papadopoulou, "Power grand composite curves shaping for adaptive energy management of hybrid microgrids," *Renewable energy,* vol. 95, pp. 433-448, 2016.

[12] B. E. Nyong-Bassey, D. Giaouris, C. Patsios, S. Papadopoulou, A. I. Papadopoulos, S. Walker, S. Voutetakis, P. Seferlis, and S. Gadoue, "Reinforcement learning based adaptive power pinch analysis for energy management of stand-alone hybrid energy storage systems considering uncertainty," *Energy,* vol. 193, p. 116622, 2020.

[13] D. Giaouris, A. I. Papadopoulos, P. Seferlis, S. Papadopoulou, S. Voutetakis, F. Stergiopoulos, and C. Elmasides, "Optimum energy management in smart grids based on power pinch analysis," *Chemical Engineering,* vol. 39, pp. 55-60, 2014.

[14] D. Giaouris, A. I. Papadopoulos, S. Voutetakis, S. Papadopoulou, and P. Seferlis, "A power grand composite curves approach for analysis and adaptive operation of renewable energy smart grids," *Clean Technologies and Environmental Policy,* vol. 17, no. 5, pp. 1171-1193, 2015.

[15] G. Byeon, T. Yoon, S. Oh, and G. Jang, "Energy management strategy of the DC distribution system in buildings using the EV service model," *IEEE Transactions on Power Electronics,* vol. 28, no. 4, pp. 1544-1554, 2012.

[16] D. Ipsakis, S. Voutetakis, P. Seferlis, F. Stergiopoulos, and C. Elmasides, "Power management strategies for a stand-alone power system using renewable energy sources and hydrogen storage," *International journal of hydrogen energy,* vol. 34, no. 16, pp. 7081-7095, 2009.

[17] J. Wang, C. Zhao, A. Pratt, and M. Baggu, "Design of an advanced energy management system for microgrid control using a state machine," *Applied energy,* vol. 228, pp. 2407-2421, 2018.

[18] C. J. Javaid, A. Allahham, D. Giaouris, S. Blake, and P. Taylor, "Modelling of a virtual power plant using hybrid automata," *The Journal of Engineering,* vol. 2019, no. 17, pp. 3918-3922, 2019.

[19] Y. Khawaja, A. Allahham, D. Giaouris, C. Patsios, S. Walker, and I. Qiqieh, "An integrated framework for sizing and energy management of hybrid energy systems using finite automata," *Applied Energy,* vol. 250, pp. 257-272, 2019.

[20] A. Kafetzis, C. Ziogou, K. Panopoulos, S. Papadopoulou, P. Seferlis, and S. Voutetakis, "Energy management strategies based on hybrid automata for islanded microgrids with renewable sources, batteries and hydrogen," *Renewable and Sustainable Energy Reviews,* vol. 134, p. 110118, 2020.

[21] A. Allahham and H. Alla, "Monitoring of a class of timed discrete events systems," in *Proceedings 2007 IEEE International Conference on Robotics and Automation*, 2007: IEEE, pp. 1003-1008.

[22] A. Allahham and H. Alla, "Monitoring of timed discrete events systems with interrupts," *IEEE transactions on automation science and engineering,* vol. 7, no. 1, pp. 146-150, 2009.

[23] M. Skoldstam, K. Akesson, and M. Fabian, "Modeling of discrete event systems using finite automata with variables," in *2007 46th IEEE Conference on Decision and Control*, 2007: IEEE, pp. 3387-3392.

[24] T. A. Henzinger, "The theory of hybrid automata," in *Verification of digital and hybrid systems*: Springer, 2000, pp. 265-292.

[25] "https://www.renewables.ninja/." (accessed 01/04/2022).

[26] "https://www.elexon.co.uk/operations-settlement/profiling/." (accessed 01/04/2022).